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Observation of Beta-Induced Alfvén Eigenmodes in the DIII-D Tokamak

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Energetic ions can drive Alfvén gap modes unstable, causing large losses of fast ions. Toroidicity-induced Alfvén eigenmodes (TAE) were expected to disappear into the shear Alfvén continuum and become stable as the plasma beta increased. Although TAE modes may disappear, another dangerous instability with similar properties but approximately half the TAE frequency appears in a spectral gap that is created by finite beta effects. The measured frequency of the new mode agrees with the theoretical frequency of beta-induced Alfvén eigenmodes.

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An ignited magnetic fusion reactor must confine charged fusion products while they thermalize. Collective modes driven by alpha particles may degrade the alpha confinement and prevent ignition in a deuterium-tritium tokamak reactor. One way to study the physics of alpha-driven instabilities is to inject deuterium neutral beams into low toroidal field deuterium plasmas. In previous experiments, beam ions destabilized toroidicity-induced Alfvén eigenmodes (TAE) in TFTR [1] and in DIII-D [2,3]. These modes are dangerous because they cause large, concentrated losses of the resonant fast ions that clamp the beam beta near the point of marginal stability [1,4]. ("Beta" is the ratio of kinetic to magnetic energy.)

TAE modes appear in a gap in the Alfvén continuum that is caused by the toroidal curvature of the plasma. The center of this "TAE gap" occurs at a frequency

$$f_{\rm TAE} = v_A/4\pi q R \,, \qquad (1)$$

where $v_A = B/\sqrt{4\pi n_i m_i}$ is the Alfvén speed, q is the safety factor, R is the tokamak major radius, B is the magnetic field, and n_i and m_i are the ion density and mass [5]. (An example of the gap structure appears in Fig. 4.) Analysis of the TAE mode suggested that its frequency would decrease into the Alfvén continuum (where it would be heavily damped) as the plasma beta approached the stability limit for ideal ballooning modes [6]. But recent calculations found a new gap underneath the Alfvén continuum caused by the compressional response of the plasma to shear Alfvén waves in the presence of finite pressure and curvature [7]. The energy associated with this compression produces a frequency shift that raises the Alfvén continuum, thus opening a low-frequency gap. Global modes in this gap with the dominant polarization of shear Alfvén waves were discovered numerically [8]; we call these modes beta-induced Alfvén eigenmodes (BAE). In this Letter, experimental evidence of destabilization of BAE modes by energetic beam ions is reported for the first time.

The experiments are performed in the DIII-D tokamak ($R \simeq 1.8$ m, $a \simeq 0.65$ m) in relatively pure ($Z_{\rm eff} \lesssim 2$) deuterium plasmas. Near tangential (tangency radius $R_{\rm tan} \simeq 1.10$ m), ~ 75 keV deuterium neutrals are injected in the direction of the plasma current; in some plasmas, near-perpendicular beams ($R_{\rm tan} \simeq 0.74$ m) are also injected. The normalized beta, $\beta_N \equiv \beta_t a B_t / I_p$, is usually near the nominal limit of $\beta_N \simeq 3.5$, although larger values can be obtained with current ramping. (Here β_t is the toroidal beta in percent, a is the minor radius in meters, B_t is the toroidal field in tesla, and I_p is the plasma current in MA.) Most of the discharges discussed here have an elongation of $\kappa \simeq 1.6$ and use the inner wall as a limiter, although divertor discharges exhibit similar behavior. The principal diagnostic for the study is an extensive array of magnetic probes mounted inside the vacuum vessel. Toroidal mode numbers n are obtained from the best fit to the phase differences of a toroidal array of eight probes. Electron temperature and density profiles are measured by Thomson scattering, the ion temperature and toroidal rotation profile is determined from charge exchange recombination spectroscopy of He II, and the q profile is obtained from the magnetic configuration, the soft x-ray inversion radii, and a single-point measurement of q using motional Stark effect polarimetry.

Figure 1 shows the evolution of the frequency of beam-driven instabilities as the beam power is increased in increments of ~ 2.5 MW. The frequency is corrected for the Doppler shift, as discussed below. With only one source (2.5 MW), no beam-driven instabilities are observed. After a second source is added at 1.7 s, TAE modes appear. At some times, two sets of peaks appear in the power spectrum simultaneously. Theoretical calculations indicate that several TAE modes with different frequencies can occupy the TAE gap, and the measured frequencies of the multiple modes agree with the calculations [8]. During this two-beam phase, the normalized beta is $\beta_N \simeq 2.8$. After the third beam is injected at 1.9 s, β_N increases to 3.3 and the frequency of the beam-driven modes drops well below the nominal TAE frequency. As we will show, these instabilities are probably BAE modes. With the addition of the fourth beam at 2.1 s, the plasma reaches the nominal beta limit ($\beta_N \simeq 3.5$) for these condi-

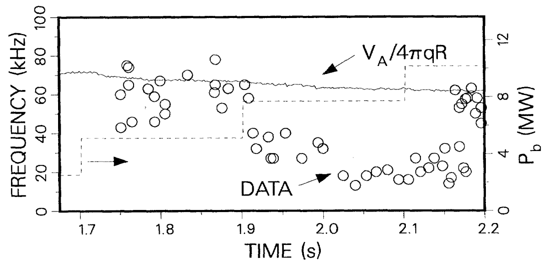

FIG. 1. Time evolution of the Doppler-corrected frequency, the nominal TAE frequency [Eq. (1)], and the beam power in shot 71524. The Doppler shift is obtained from the spacing of peaks with different mode numbers, as in Fig. 3(b); the uncertainty in frequency is typically 5 kHz. The gradual decrease in $f_{\rm TAE}$ is caused by an increase in electron density during beam injection. [Here, and in Figs. 2 and 5, the nominal values $q=1.5$, $R=1.7$ m, $n_i=\bar{n}_e$, and $B=B_t$ are used for $f_{\rm TAE}$ in Eq. (1). Measurements [2] of the eigenfunction peak near the $q=1.5$ surface in some cases.]

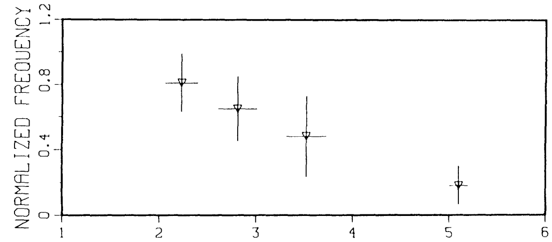

FIG. 2. Doppler-corrected frequency divided by $f_{\rm TAE}$ as a function of β_N for many discharges. The error bars represent the standard deviation of the data.

tions. At about 2.16 s, the low frequency magnetohydrodynamics (MHD) activity of the plasma changes from predominately $n=1$ modes (fishbones and sawteeth) to predominately $n=2$ (tearing mode) activity. As this transition takes place, both TAE activity and BAE activity occur. Later, the BAE activity disappears altogether and only TAE modes are observed. (This transition back to TAE activity late in the discharge is relatively unusual [9].)

The mode frequency tends to decrease with increasing β_N, as shown in Fig. 2. In this figure, the Doppler-corrected frequency is normalized to $f_{\rm TAE}$. The data are from sixty discharge conditions that span the parameter range $I_p=0.4$–1.0 MA, $B_t=0.7$–1.4 T, $\bar{n}_e=(1.1$–$5.5)\times 10^{13}$ cm^{-3}, $P_b=2.5$–16 MW, $\kappa=1.1$–2.2, and $\beta_t=1.5\%$–6.7%. For modest values of normalized beta ($\beta_N \lesssim 2.5$), the measured frequency agrees with $f_{\rm TAE}$ within $\sim 25\%$. Three known sources of error contribute to the scatter in $f/f_{\rm TAE}$. First, the uncertainty in the Doppler-shift correction is $\sim 10\%$. Second, the experimental value of q need not equal the value of 1.5 assumed in $f_{\rm TAE}$. Third, the actual mode frequency does not necessarily lie in the center of the gap, as assumed by Eq. (1). For a toroidal field scan where the changes in plasma profiles are minimized, the scatter in $f/f_{\rm TAE}$ is reduced to 12%.

As the normalized beta increases, the ratio of $f/f_{\rm TAE}$ drops and the scatter becomes larger (Fig. 2). At the nominal beta limit of $\beta_N \simeq 3.5$, the frequency is usually less than half the expected TAE frequency, although occasionally larger values are observed (as in Fig. 1 after 2.16 s). The data with $\beta_N \simeq 5.2$ in Fig. 2 are from a single discharge with a strong negative current ramp, so it is not certain if such a low value of $f/f_{\rm TAE}$ is always observed for these conditions. The decrease of $f/f_{\rm TAE}$ with β_N is one of the strongest dependences observed in our data set (the correlation with the poloidal beta β_p is similar); in particular, the dependences upon β_t, κ, $\bar{n}_e$, I_p, B_t, v_A, and the beam beta β_b are all weaker.

The Doppler-shift correction for TAE modes has been studied extensively and will be reported elsewhere. In brief, the correction $\delta\omega$ can be obtained either from measurements of the toroidal rotation profile or from fits to the toroidal mode number spectrum. The first method assumes that helium impurities rotate with the same velocity as the bulk deuterium plasma and that the poloidal rotation velocity v_θ is much smaller than the toroidal rotation v_ϕ so that $\delta\omega \simeq n v_\phi/R$. The second method assumes that TAE modes with different toroidal mode numbers rotate with the same speed v_ϕ and have identical frequencies in the plasma frame. The two methods agree well (to within $\sim 10\%$) and with theoretical calculations of the TAE frequency [3]. Since the structure of BAE modes resembles the structure of TAE modes (see below), these techniques are valid for BAE modes as well.

Figure 3(a) shows the cross-power spectrum of two toroidally separated magnetic probes at 2.177 s in the discharge of Fig. 1. The momentum input from the

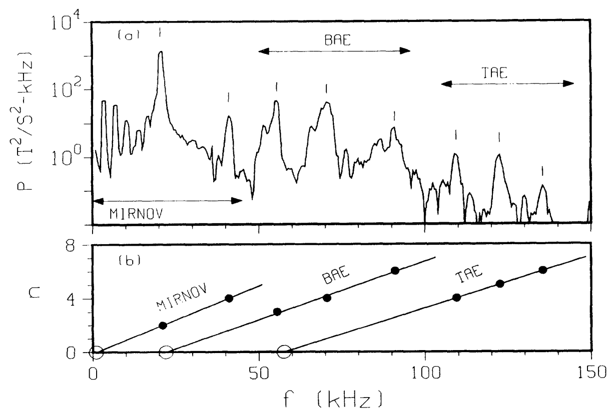

FIG. 3. Power spectrum (a) and toroidal mode number spectrum (b) for magnetic fluctuations at 2.176–2.178 s in shot 71524. The open circles in (b) indicate the inferred mode frequencies in the plasma rest frame. $B_t=0.8$ T, $I_p=0.6$ MA, $P_b=10$ MW, $\bar{n}_e=3.8\times10^{13}$ cm^{-3}, $T_e(0)\simeq 1.8$ keV, $T_i(0)=2.6$ keV, $\beta_N=3.5$, $\beta_p\simeq 1.5$.

beams causes the plasma to rotate toroidally at ~ 11 kHz and introduces Doppler shifts in the spectrum. Three sets of peaks are observed. The first set of low-frequency peaks (labeled "Mirnov") are the usual set of peaks associated with MHD activity that is nearly stationary in the plasma frame. A plot of the toroidal mode number n of these peaks versus the observed frequency falls on a straight line; this line intercepts the frequency axis near the origin [Fig. 3(b)]. In this discharge, the TAE modes appear above 100 kHz. The Doppler-corrected frequency inferred from the toroidal mode number spectrum [the frequency-axis intercept in Fig. 3(b)] is 58 kHz. The peaks between 50 and 100 kHz are the new feature associated with BAE modes. The BAE modes have toroidal mode numbers that are similar to TAE modes (typically $n=2$–8) and the mode number spectrum intercepts the frequency axis at 22 kHz.

Comparison of the measured frequencies with the theoretical spectrum of Alfvén modes is consistent with identification of the low-frequency peaks as BAE modes. Figure 4 shows the Alfvén continuum spectrum calculated by the CONT code [7] for $n=3$ modes. Finite beta creates an additional gap beneath the lowest continuum branch. It also complicates the spectrum by coupling the

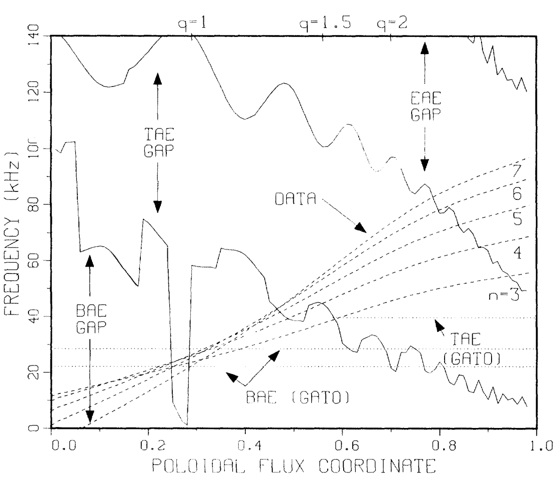

FIG. 4. Doppler-corrected frequency f (dashed curves) versus ψ for shot 71524 at 2.1475–2.1495 s. The numbers are the toroidal mode number of each mode. The corrected frequency is obtained from the measured frequency $f_{\rm lab}$ and the toroidal rotation velocity v_ϕ using the formula $f = f_{\rm lab} - nv_\phi/2\pi R$; the error in the spline fit to the rotation profile is approximately $\pm 5\%$, which propagates into a $\sim 5\%$ error in the Doppler-shift correction. Uncertainty in the equilibrium reconstruction is estimated to yield variations in the curves of 5%–10%. The solid lines are the $n=3$ Alfvén continuum calculated by the CONT code [7] for the same equilibrium. (The envelope of the curves is similar for higher values of n [7].) The dotted lines indicate the frequencies of BAE and TAE modes calculated by GATO. (Several modes are found in each gap [8].)

shear Alfvén waves to sound waves. This coupling is responsible for the sharp jumps in the continuum curves in Fig. 4; nevertheless, the general envelope of the Alfvén continuum is evident. Also shown as horizontal lines in Fig. 4 are the frequencies calculated by the ideal MHD stability code GATO for $n=3$ BAE and TAE modes. The calculated BAE modes have radially extended eigenfunctions which peak in the plasma interior. These modes have the dominant polarization of Alfvén waves ($\xi_\perp > \xi_\parallel$, where ξ is the displacement vector) [8].

The Doppler-corrected experimental mode frequency is shown as a function of minor radius in Fig. 4 for several beam-driven modes. Here the plasma rotation speed profile $v_\phi(r)$ is used to calculate the mode frequency in the frame rotating toroidally with the plasma at radius r. This Doppler-corrected frequency should equal the theoretical frequency at the radial location of the mode. The Doppler-corrected frequencies agree with the calculated BAE frequency near the $q=1$ surface, where the BAE frequency calculated by GATO lies in the beta-induced spectral gap and where the calculated BAE eigenfunction has its maximum amplitude.

Although the experimental curves also pass through the toroidicity-induced gap between the $q=1.5$ surface and the plasma edge, they probably do not represent TAE modes excited in the outer part of the discharge. GATO calculations indicate that TAE modes can exist in this edge region, but the eigenfunctions peak near the $q=2.5$ surface and do not extend into the plasma interior. Since the calculated fast-ion driving rate is very small outside the $q=2$ surface [3], these edge modes are probably stable. (At lower values of β_N, the calculated TAE modes that agree with experiment have eigenfunctions that peak in the interior [8].) Soft x-ray measurements confirm that the BAE modes are excited in the center of the plasma. For these experiments, the two soft x-ray arrays measure inward displacements and vertical displacements. Analysis of the data indicates displacements of $\mathcal{O}(0.1$–$1)$ mm, with similar values observed for the high-frequency (TAE) modes and the low-frequency (BAE) modes. In both cases, the profile is globally extended and the largest displacements occur for $q < 1.5$.

The frequency of BAE modes increases linearly with toroidal field, as expected for Alfvén waves. Figure 5 shows the Doppler-corrected frequency as a function of Alfvén speed for a scan of toroidal field in discharges with similar shapes and densities. The data during heating with two sources ($P_b \simeq 5$ MW) agree to within 20% with the expected scaling for TAE modes [3]. During the four-beam phase ($P_b \simeq 10$ MW), the frequency still increases with increasing Alfvén speed, but the slope is $\sim \frac{1}{2}$ as large. The frequency of BAE modes calculated by GATO also increases linearly with v_A and is consistent with the experimental observations. In contrast, the data do not scale with ω_{*e}, with $\sqrt{T_i}$, or with $\sqrt{T_e}$, as would be expected for drift waves, acoustic modes, or semicol-

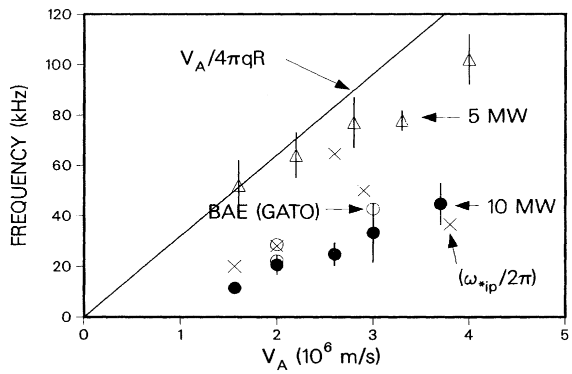

FIG. 5. Doppler-corrected frequency versus the Alfvén speed during a scan of the toroidal field from 0.6 to 1.4 T in discharges like shot 71524. The error bars indicate the standard deviation of the frequency for several times near 1.85 s (triangles) or 2.15 s (solid). At 10 MW, β_N varies from 3.0 to 3.5. Also shown is the nominal TAE frequency (solid line) and the frequencies of BAE modes calculated by GATO (circles). The ion diamagnetic frequency (×) is evaluated at the $q=1$ surface using spline fits to the measured T_i, n_e, and $Z_{\rm eff}$ profiles and the approximation $k_\theta = nq/r$, where n is the toroidal mode number of the largest amplitude mode and r is the minor radius.

lisional Alfvén modes [10]. The frequency also does not scale with the ion diamagnetic frequency ω_{*pi} (Fig. 5). Nominally, the frequency of kinetic ballooning modes scales with ω_{*pi} [11], although recent work suggests the predicted mode frequency falls to $\omega_{*pi}/2$ near the beta limit [12]. Although the data do fall within this range, the linear scaling with v_A suggests an Alfvén wave.

23 power spectra with multiple sets of peaks have been observed (cf. Fig. 3). For the cases where the frequency of the strongest mode is comparable to $f_{\rm TAE}$, the frequencies of the two modes differ by $(12\pm 6)\%$, indicating that both modes lie in the TAE gap. In contrast, when the frequency of the strongest mode is $< \frac{1}{2} f_{\rm TAE}$, the frequencies differ by $(44\pm 15)\%$. For these cases, the stronger mode lies in the BAE gap, while the weaker mode resides in the TAE gap.

Beam-driven instabilities usually "saturate" in a relaxation cycle about the point of marginal stability; the saturation occurs when the fast ions that drive the instability are expelled from the plasma by the instability [13]. Analysis of the nonlinear cycle yields information about the damping rate of the instability and about the mechanism of fast-ion loss [13]. When the frequency of the unstable mode drops from the TAE gap to the BAE gap as in Fig. 1 at 1.91 s, the nonlinear cycle does not suddenly change but gradually evolves. This suggests that the damping rate and particle losses do not differ greatly for the two instabilities. The drop in neutron emission caused by beam-ion loss is comparable for TAE and BAE modes with similar mode amplitudes. These observations are consistent with the hypothesis that both instabilities are Alfvén gap modes with spatially extended eigenfunctions.

In summary, a beam-driven instability with a frequency less than half the TAE frequency is observed as the plasma approaches the beta limit. The frequency of the instability lies below the gap in the Alfvén continuum occupied by TAE modes, in a new gap that is created by finite beta effects. The following observations suggest that the instability is a BAE mode. (1) The mode frequency scales linearly with the Alfvén speed. (2) The mode is only observed at large β_N. (3) The mode frequency agrees well with the calculated frequency of BAE modes and lies in the BAE gap. (4) The mode structure, nonlinear cycle, and fast-ion losses are similar to TAE modes.

The observation of these modes dashes hopes that Alfvén instabilities can be avoided by operating near the beta limit. Experimentally, the BAE mode seems just as deleterious as the TAE mode. Future theoretical and experimental work should concentrate on understanding the stability properties of this new instability. Control of BAE modes in a reactor may require operation in a regime that minimizes the alpha-particle pressure (low T_e and high n_e) or modification of the Alfvén gap structure to increase mode damping [3].

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